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Feasibility of a $Si_{1-x}Ge_x$ THz Resonant-State Laser

Yu. P. Gousev, I. V. Altukhov, M. S. Kagan, V. P. Sinis, H. K. Olsson, S. G. Thomas, and K. L. Wang

Abstract **– We report on pulsed THz emission from $Si_{1-x}Ge_x$ structures. d-doped with Boron $Si_{1-x}Ge_x$ layer was sandwiched between two Si layers grown by MBE on n-type Si substrate. Optical resonator was formed by high-accuracy polishing of lateral facets. Non-thermal emission was observed at electric field > 250 V/cm and pulse duration was < 1 μs. We believe the emission is due to the population inversion of carriers in the $Si_{1-x}Ge_x$ quantum well.**

I. Introduction

Recently emerged Ge resonant-state laser (RSL) [1-5] represents, among the molecular gas laser and p-Ge (or p-Si) laser, a radiation source which can cover the entire frequency range between 2 and 10 THz. Unlike of that of the molecular laser, operation frequency of the RSL can be set to virtually any value within this range. Another feature of the RSL is that, due to the origin of population inversion, it requires relatively low electric field which gives a possibility to operate it in the cw regime [4,5].

Population inversion in the RSL is realised for the states of a shallow acceptor split under external stress. If the strain is high enough, the split-off acceptor state enters

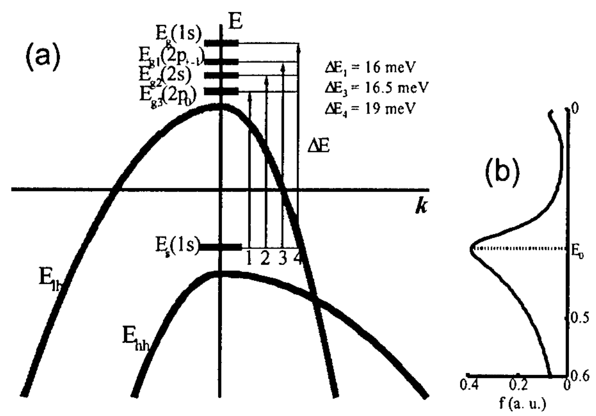

Fig. 1: Possible optical transitions and distribution function of holes under applied electric field for a case of strained Ge [4].

the light-hole branch of the valence band and creates a resonant state. For the case of Ge doped with Ga, external stress should be above ~3 kbar. Electric field, which is also necessary for population inversion, provides emptying the ground state due to the impact ionisation. Schematic diagram for possible optical transitions in this case is given in Fig. 1 [4]. The frequency range covered by the RSL is determined by the threshold stress necessary for creating the resonant state, and the maximum useful stress at which optical phonon-assisted hole transitions to the valence band depopulate the resonant state. Thus, for Ga- or B-doped Ge, the operation frequency can be set to any value between ~ 2 and 10 THz.

An alternative way to realise RSL is to use a p-doped binary alloy of elements having similar to that of Ge structure of valence band, like $Si_{1-x}Ge_x$. In such an alloy, strain is induced internally due to the lattice mismatch. Therefore, acceptor levels are split without external stress, and stimulated emission can be obtained just by adding electric field.

II. How a $Si_{1-x}Ge_x$ Laser Should Function

Population inversion mechanism in $Si_{1-x}Ge_x$ should be similar to that in Ge. However, conventional $Si_{1-x}Ge_x$ technology processes use for fabrication Si wafers which gives advantages of easier Si (unlike Ge) processing and simpler integration with Si-based electronics. In this case, x has to be relatively low, and initial position of the acceptor state in the energy gap is close to the acceptor ionisation energy in Si. Since the ionisation energy of Ga or B in Si is larger compared to that in Ge, one should induce higher strain to create the resonant state.

Ionisation energy of B is about 45 meV in Si, and about

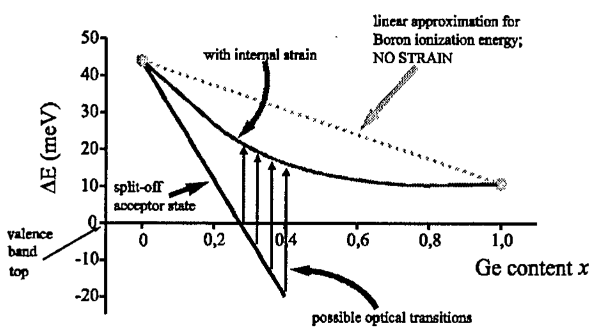

Fig. 2: Possible optical transitions for SiGe.

11 meV in Ge. An approximate diagram for acceptor energy levels in $Si_{1-x}Ge_x$ is shown in Fig. 2. Here, we assumed that ionisation energy is changed linearly with Ge content x in case of no strain is induced, and then made correction for the strain effect. In order to create a resonant state, the split-off acceptor state must enter the valence band continuum. Which means, x has to be larger than ~ 0.25. For such a high Ge content, $Si_{1-x}Ge_x$ layer grown on Si becomes unstable, and realisation of the $Si_{1-x}Ge_x$ RSL seems problematic.

III. Experimental Results

20 nm thick d-doped with Boron $Si_{1-x}Ge_x$ layer was

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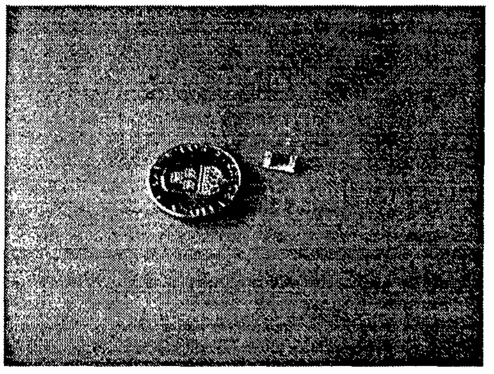

Fig. 3: Sample view. For scale, 1 Kr is shown.

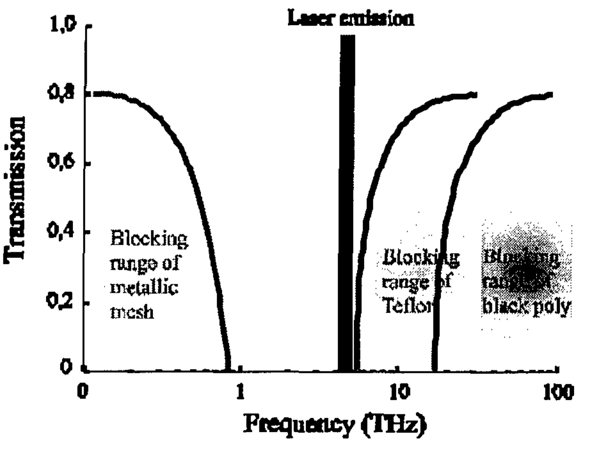

Fig. 5: Frequency characteristics of filters.

sandwiched between two, 60 and 130 nm thick, Si layers grown by MBE on the n-type Si substrate; x was equal to 0.15. Ohmic contacts to the quantum well have been made by the thermal diffusion process. Lateral facets of the crystal were high-accuracy polished. Sample view is given in Fig. 3; a 1 Kr coin is shown for scaling.

Measurements of far-IR emission from the samples have been made at 4.2 K. Pulsed bias voltage up to 2000 V was applied to the sample. Pulse duration was typically about 1 μs; repetition frequency 1 to 10 kHz. Both voltage and current applied to the sample were measured during the pulse.

Block diagram for experimental set-up is shown in Fig. 4. Emission was detected with a cooled Ge:Ga detector. To avoid RF and near-IR interference, we used a set of filters; frequency characteristics of filters are shown in Fig. 5. While the metallic mesh, used as a high-pass filter, was installed permanently, IR Teflon and black polyethylene filters were exchanged for a check if there is any contribution to the signal at frequencies above the range of interest. No IR contribution was found with an accuracy of 10 %.

Signal voltage, measured across a resistor connected in series with the detector crystal, was amplified with a low noise amplifier and registered with an oscilloscope. We found that high-intensity emission appeared at bias voltage between 250 and 700 V/cm (Fig. 6). Signal voltage up to 100 mV before amplification has been

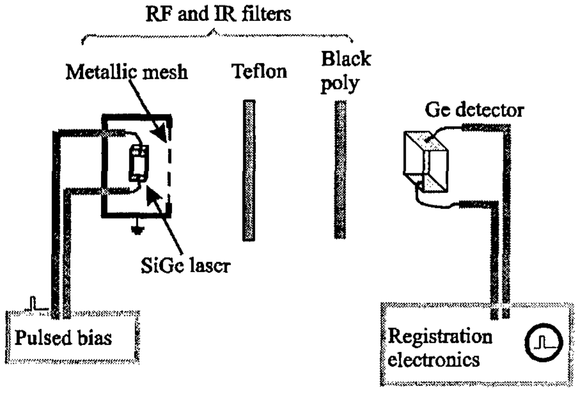

Fig. 4: Experimental set-up.

observed. We believe that difference in the threshold voltage was due to the poor quality of ohmic contacts. Above threshold voltage, intensity increased drastically by more than an order of magnitude. Since the form of the registered intensity pulse was identical to that of bias voltage for pulse duration < 1 μs, we suppose the emission is not due to any thermalisation process. We believe that observed signal corresponds to the stimulated emission from the $Si_{1-x}Ge_x$ layer.

The question why stimulated emission is observed at low value of x, requires further investigation. Possible explanation for the origin of population inversion follows from temperature dependence of conductivity of $Si_{1-x}Ge_x$ quantum wells presented in [6]. The resonant state can arise in the valence band at lower strain due to the tunneling of holes from the split-off acceptor state to the valence band, if a transverse electric field is present. The latter might be created by the surface charge.

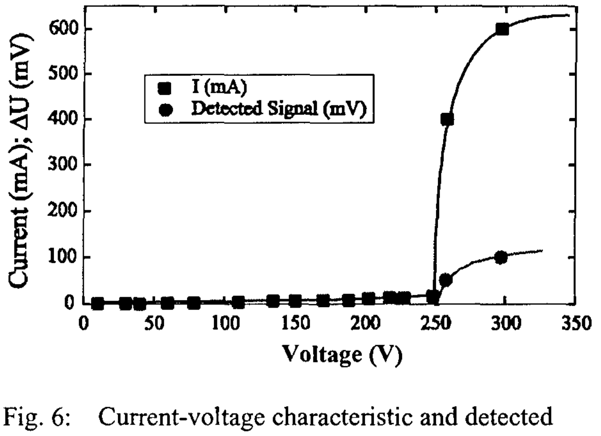

Fig. 6: Current-voltage characteristic and detected signal.

IV. Conclusion

We have shown that high-intensity THz emission is generated by $Si_{1-x}Ge_x$ quantum wells at low temperatures if a high-quality optical resonator is used for optical confinement. The non-thermal origin of emission proves feasibility of a $Si_{1-x}Ge_x$ resonant-state laser.

Acknowledgement

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